

The 7th International Conference on Applied Energy – ICAE2015

Transient simulation of a Dual-evaporator air conditioning system for developing an improved humidity control strategy

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This paper presents a mathematic model for predicting the dynamic performance and developing an improved humidity control strategy of a Dual-evaporator air conditioning (DEAC) system. The model is built based on component sub-models. Using the DEAC model developed, simulation studies were carried out under multi-evaporator operation and single-evaporator operation, respectively. Dynamic effects of the multi-evaporator operation suggested that the model developed could predicate the transient performance of the DEAC system over a wide range of operating conditions. Therefore, it can be used as a useful tool in investigating the control performance of a DEAC system. A previously developed High-Low control strategy for improved indoor humidity control was incorporated into the developed DEAC model. At the first stage, only the single-evaporator operation under the H-L control was simulated. The simulation study has produced similar results to the previously experimental results on H-L control and thus paved the way to studying applying the H-L control to a DEAC system for better indoor humidity control.

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Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: DEAC; Modeling; High-Low control strategy; Transient performance; humidity control

1. Introduction

Multi-evaporator air conditioning (MEAC) systems featuring variable refrigerant flow are becoming increasingly attractive. This is because the use of MEAC systems offers many advantages such as installation convenience, higher design flexibility, better thermal comfort control and higher energy efficiency [1]. Although the developments in capacity controllers for MEAC systems have been reported, most of them focused on controlling indoor air dry-bulb temperature and, therefore no previous studies on controlling both indoor air temperature and humidity may be identified.

In a hot and humid region such as Hong Kong, the requirement for removing moisture from air can be often more demanding than removing the sensible load. Previous study results suggested that an

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appropriate indoor humidity level could be maintained by simultaneously varying the speeds of the compressor and the supply fan in a single evaporator air conditioning (SEAC) system [2]. In order to improve the control of indoor humidity using MEAC systems, a new control algorithm should be developed. A large number of thermodynamic models for heat pumps/ refrigerators are available. Notable works include fully lumped parameter models [3], fully distributed models [4] and partial-lumped parameter models [5]. It is however noted that, almost all previous model development work reported focused on SEAC systems [3]. Chen et al. [6] developed a simplified dynamic model for a triple evaporator air conditioning (TEAC) system using partial-lumped parameter modeling approach. However, no experimental validation for the model was conducted and only sensible heat balance equations of evaporators were included in the developed model.

This paper reports on the development of a transient mathematical model of an MEAC system and a simulation study on a novel control strategy to improved indoor humidity control, using the model developed. When carrying out the simulation study on developing the control strategy for improved indoor humidity, a previously developed control strategy for a SEAC system for improved humidity control, High-Low (H-L) speed control [7], is applied, for determining the speeds of the compressor and indoor air fans. However, in this paper, the H-L control strategy to an SEAC system is presented. Since the study on applying the strategy to a DEAC system is underway and will be reported in future.

Since an MEAC system can have any number of evaporators, a dual-evaporator air conditioning (DEAC) system, using R22 as refrigerant, is used here as a typical example for modeling and controller development. A schematic diagram of the DEAC is shown in Fig. 1.

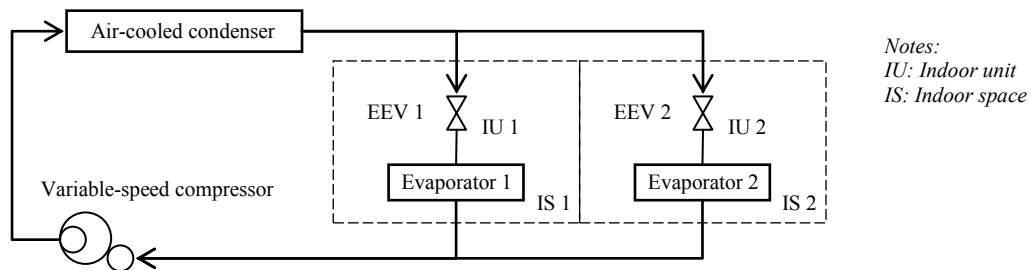


Fig. 1 The schematic diagram of a DEAC system

Nomenclatures

A	heat transfer area (m^2)	P	pressure (Pa)
C_p	specific heat ($\text{kJ}/(\text{kg} \cdot \text{K})$)	\dot{Q}	heat transfer heat (W)
g	air moisture content (kg/kg dry air)	T	temperature ($^{\circ}\text{C}$)
h	enthalpy (J/kg)	V	volume (m^3)
m	mass flow rate (kg/s)	W	moisture load (kg/s)
α	heat transfer coefficient ($\text{W}/(\text{m}^2 \cdot \text{K})$)		

2. Dynamic model development

A conceptual model of a DEAC system is given in Fig. 2. As seen in Fig. 2, the key system components to be modeled include a variable-speed compressor, two indoor units (IU), and an air-cooled condenser. In each IU, there is a direct expansion (DX) evaporator, an electronic expansion valve (EEV) and a supply fan. The mathematic sub-models for these key components are developed respectively by reference to the component sub-models built by Deng [6]. Then these component sub-models are connected to form a complete system model.

The well-known Cleland correlations and the air state correlations recommended by the ASHRAE were used to describe the properties of R22 and air, respectively.

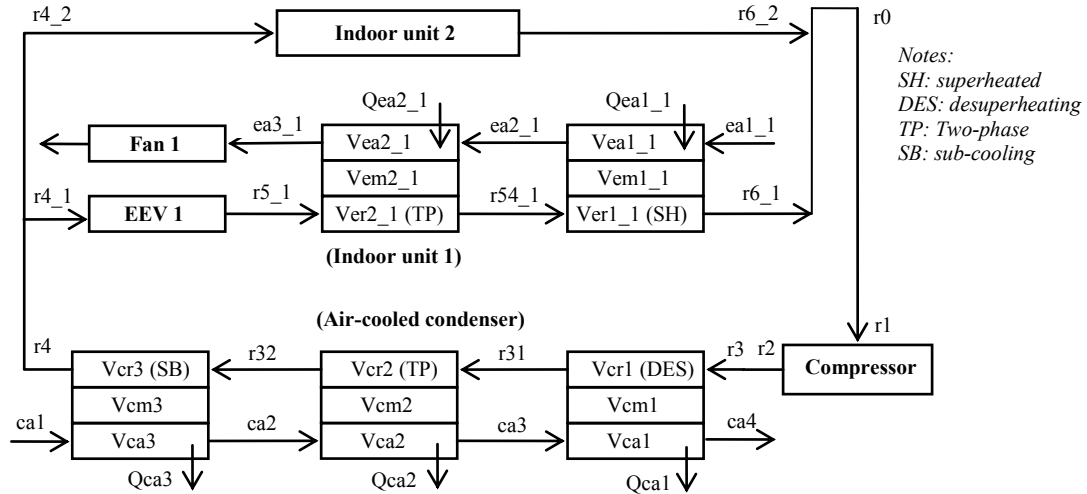


Fig. 2 Conceptual model of a DEAC system

2.1. Sub-models for key system components

A compression process and isenthalpic throttling process was assumed when modeling the compressor and EEVs, respectively.

Both the condenser and evaporators were approximated to be ideal counter-flow heat exchangers. According to the state of refrigerant, a heat exchanger was divided, when modeling, into several regions. In each region, the heat and mass transfer of refrigerant side and air side were separately modelled. The log mean temperature difference (LMTD) method was applied to each region of the heat exchangers to determine their heat transfer rates. Taking the superheated region of an evaporator V_{er1_1} as an example, mass and energy balances yielded:

$$m_{r6_1} = m_{r54_1} \quad (1)$$

$$Q_{er1_1} = m_{r6_1} h_{r6_1} - m_{r54_1} h_{r54_1} \quad (2)$$

The heat transfer rate between the refrigerant and the tube wall in the superheat region was given as:

$$Q_{er1_1} = \alpha_{er1_1} A_{er1_1} LMTD_{er1_1} \quad (3)$$

2.2. Sub-model for indoor space

In order to carry out the simulation study using the model developed, sub-models for the two indoor spaces (IS) were also developed. It was assumed that throughout an IS, both indoor air temperature and moisture content were the same as these at the evaporator inlets, T_{ea1} and g_{ea1} . For an indoor space i ($i=1, 2$), its space internal energy and mass balance equations were:

$$\rho_a V_i C_p \frac{dT_{ea1_i}}{dt} = Q_i - \rho_a V_{ea_i} C_p (T_{ea1_i} - T_{ea3_i}) \quad (4)$$

$$\rho_a V_i \frac{dg_{ea1_i}}{dt} = \rho_a V_{ea_i} (g_{ea1_i} - g_{ea3_i}) + W_i \quad (5)$$

2.3. Model solution

In the DEAC system, two IUs are connected in parallel without any pressure regulators. Therefore, the pressure at each evaporator outlet should be the same.

$$P_{r6_1} = P_{r6_2} \quad (6)$$

It was also assumed that the mixing of refrigerant leaving the two evaporators was perfect, without energy loss.

$$m_{r6_1} + m_{r6_2} = m_{r1} \quad (7)$$

$$m_{r6_1} h_{r6_1} + m_{r6_2} h_{r6_2} = m_{r1} h_{r1} \quad (8)$$

In addition, geometrical parameters of all components were the input to the model. Initial values were also required as a starting point for a transient simulation. These include the evaporating and condensing pressures, space volumes of heat exchangers' two-phase region, evaporators and the condenser inlet air conditions, etc.

Totally, the DEAC model consists of sixty-two equations, with seventeen of them being first-order ordinary differential equations. In addition, there were seventeen equations on thermal properties of R22 and air. The differential equations were solved using the Euler integration approach.

The challenge in modelling MEAC systems came from the coupling of evaporators operated at a similar pressure but different refrigerant mass flow rates [8]. Therefore, a mass flow distribution strategy should be provided. In the current study, the refrigerant mass flow rate to each of the two IUs was determined in proportion to its cooling capacity.

3. Results and discussion

Using the DEAC model developed, simulation studies were conducted under two typical operating conditions: under multi-evaporator operation to investigate the system dynamics and under single-evaporator operation to investigate the effects of applying the H-L control algorithm for improved humidity control. These are reported as follows.

3.1. Multi-evaporator operation

The simulation results suggested that the dynamic variation of key system parameters such as states of indoor air, evaporating and condensing pressures, etc. changed with the indoor space loads, speeds of compressor and the two indoor air fans.

An example of simulated transient responses of the DEAC system is shown in Fig. 3. In the first 150 seconds, air mass flow rates for both IUs are constant at 0.125 kg/s. At 150 s, the air mass flow rate in IU 2 is reduced from 0.125 kg/s to 0.08 kg/s. As seen from the figure, both evaporating pressures and supply air temperatures from IUs start to decrease at that time with load reducing in IU2. 150 seconds after the change, they reach new steady state conditions.

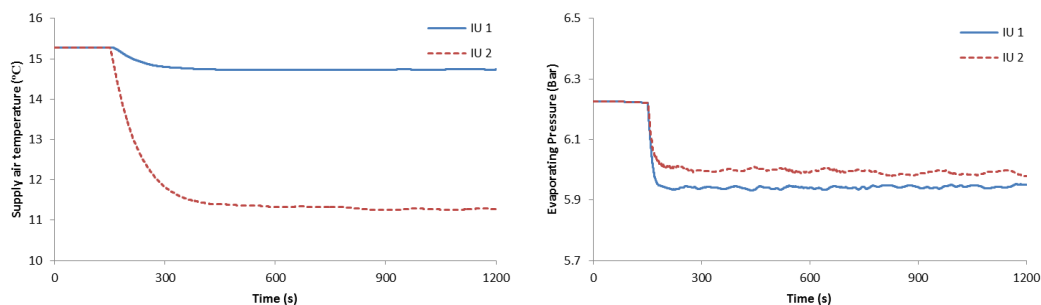


Fig. 3 (a) Model response — supply air temperature; (b) Model response — evaporating pressure

Because of the differences in each indoor unit's capacity and operational condition, the changes in operational parameters in one indoor unit are likely to influence those in the other. Therefore, even the operating conditions of IU 1 remained unchanged, its performance parameters also varied if there are changes in IU 2's operation.

The results of model tests suggest that the model developed is stable and behaves as expected. Therefore, it can be used as a useful tool in investigating the control performance of an MEAC system.

3.2. Single evaporator condition

In this simulation study, the previously developed H-L control strategy for improved indoor humidity control was incorporated into the developed DEAC system. As the first step of the control strategy development for improving humidity control using an MEAC system, an SEAC system under the H-L control was simulated by shutting down one IU.

The H-L control strategy [7], which enables both the compressor and the supply air fan in a DX A/C system to operate at high speeds when the indoor air-dry bulb temperature setting is not satisfied and at low speeds otherwise, was successfully used to control a SEAC system. Experimental results [7] reveal that the use of H-L control strategy would result in better control performance in terms of an improved indoor humidity level and higher energy efficiency compared with the use of traditional on-off control strategy.

In a SEAC system, for its IU, with its indoor air temperature setting, T_{set} , a control signal at a time point t , $E(t)$, can be defined as:

$$\begin{aligned} \text{If } T(t) &\geq T_{set} + \Delta T & E(t) &= 1 \\ \text{If } T_{set} - \Delta T &< T(t) < T_{set} + \Delta T & E(t) &= E(t-1) \\ \text{If } T(t) &\leq T_{set} - \Delta T & E(t) &= 0 \end{aligned} \quad (9)$$

Where $T(t)$ is the actual space air temperature at t time point, $t-1$ the last time point and ΔT the temperature control dead band (e.g., 0.7 °C).

The period when $E(t)=1$ is referred to as an H-period when the compressor and fan are operated at higher speeds and that when $E(t)=0$, low speed period. The refrigerant mass flow rate entering an evaporator is controlled by an EEV. When $E(t)=1$, EEV functions to control the refrigerant degree of superheat. At the same time, the supply fan will operate at the full speed. On the other hand, when $E(t)=0$, EEV functions as a modulating valve to reduce the refrigerant mass flow rate supply to supply less refrigerant to an IU. At the same time, the supply fan speed is also reduced to result in a small supply air flow rate.

The above control algorithms were integrated into the DEAC model developed, and the simulated control performance are shown in Fig. 4. In the simulation, T_{set} was set at 26 °C with a dead band of 0.7 °C. As seen, the indoor air temperature fluctuates around the setting point in a repeatable pattern. The fluctuation range of the indoor air relative humidity (RH) is relatively small, at around 2%. These simulation results were similar to the experimental results reported previously and it is therefore interesting to look at applying the strategy to the DEAC system.

Further simulation studies on applying the H-L control strategy to the DEAC system will be carried out and the study results will be reported once available.

4. Conclusion

This paper presents the development of a dynamic mathematical model for a typical MEAC system, a DEAC system. The system components modelled included a variable-speed compressor, an air-cooled condenser, EEVs and evaporators, etc. The model can predicate the transient performance of the DEAC

system over a wide range of operating conditions. Using the model developed, a simulation study on applying the previously developed H-L control strategy for improved indoor humidity to an SEAC system, as a first step, is reported. The simulation study has produced similar results to the previously experimental results on H-L control and thus paved the way to studying applying the H-L control to a DEAC system for better indoor humidity control.

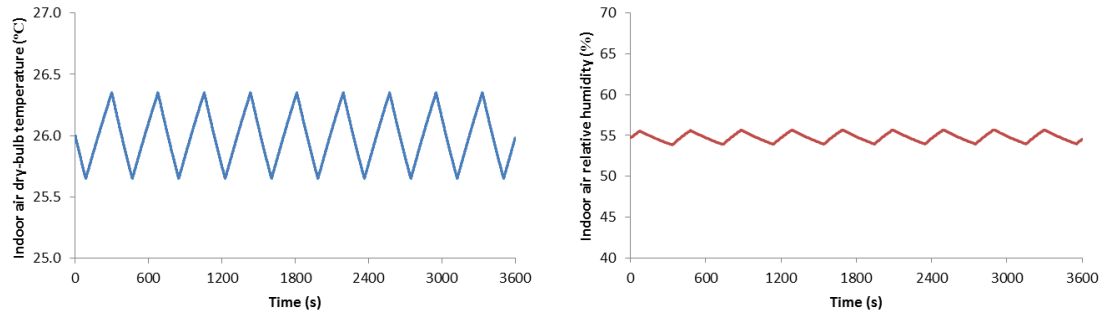
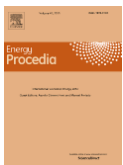


Fig. 4. (a) Variation of indoor air dry-bulb temperature; (b) variation of indoor air relative humidity

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Biography

Prof. Deng Shiming is currently a professor and associate head of the Department of Building Services Engineering at The Hong Kong Polytechnic University. He obtained his PhD from South Bank Polytechnic, London in 1991 and His research focuses on the modelling and control of refrigeration and air conditioning systems.